PROCESSING, FABRICATION, AND DEMONSTRATION OF HTS INTEGRATED MICROWAVE CIRCUITS

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R&D STATUS REPORT

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DESCRIPTION OF PROGRESS

TASK 1.0: COMPARATIVE TECHNOLOGY ASSESSMENT

This task is essentially complete, but we are continuing to monitor progress in other technologies as they relate to the goals of this program.

TASK 2.1: INTEGRATED SUBSYSTEM SPECIFICATIONS

- Non-Linear Distortion in Filters

Further measurements of nonlinear distortion in HTS filters were made during this reporting period. Third-order spurious intermodulation products were measured at 77K for one of the channels (center frequency near 4 GHz) in the filterbank made recently for the Navy HTSSE-II program. This was done to determine if the improved quality of our films will reduce the distortion in devices. The results are shown in Figure 1, where the measurements are plotted on the same graph as those for the X-band filter at 77K, included in last quarter's report. Fewer points were taken, and over a narrower range of input power levels than was the case for the X-band filter in order to utilize only the maximum sensitivity of the spectrum analyzer and minimize its contribution to the intermodulation distortion measured. Similar measurements made recently on the X-band filter agreed with those previously taken. As can be seen from Figure 1, the data taken in this fashion follow a 3:1 slope, giving a third-order intercept point of 35 dBm for the newer, 4 GHz filter compared with 20 dBm for the older, X-band filter. Assuming that the nonlinear behavior is independent of frequency, we attribute the lower third-order spur level of the newer filter to the higher quality of the YBCO films grown now compared to those grown in 1990, when the X-band filter was made. Table I compares the growth techniques used then with those currently used. The most significant feature of the new films is the elimination of the CuO particulates on the film surface. Earlier films, from

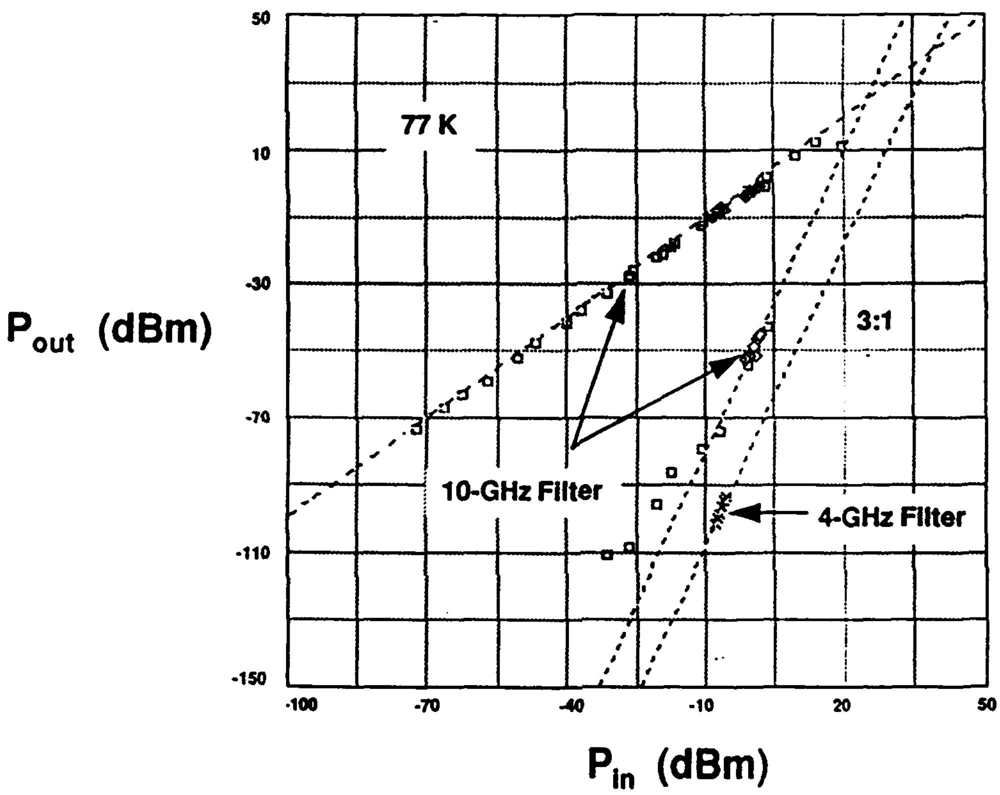

Figure 1 — Nonlinear filter response at 77K. The 10 GHz filter was made from a film grown in 1990. The 4 GHz filter is one of the channels made recently for the parallel HTSSE-II program. The film used for this device is of superior quality to those grown in 1990.

Table I - YBCO Growth Technique Differences

	1990	Current
Sputtering	DC	RF
Growth Temp.	650 C	700 - 750 C
Substrate Heating	Silver-Painted	Radiation
Substrate Size	Small Chips	2-inch Dia.
Surface Quality	High Density of CuO Particles	Smooth

which the X-band filters were made, had a high density of CuO "boulders" while those grown today are quite smooth and featureless.

- Noise Figure Measurements in Filters

Noise figure was measured at 77K in this reporting period for the X-band filter used in the intermodulation distortion experiments. As shown in Figure 2, the noise figure follows closely the predicted behavior (Mumford and Scheibe, "Noise Performance Factors in Communication Systems," Horizon House 1968):

$$F = 1 + (L - 1) \frac{T}{290} \qquad (1)$$

where F is the noise figure, L the insertion loss (both expressed as a fraction), and T is the operating temperature in Kelvin.

The equipment used for these measurements comprised a noise figure meter, a frequency synthesizer, and a noise source. It allowed the determination of insertion loss as well as noise figure as a function of frequency.

These measurements on a device fabricated with the poorer quality films of 1990 having a high density of CuO precipitates can be considered a worst case. They confirm that the noise figure of a passive superconducting device is as predicted from thermal noise considerations and that HTS devices offer a system noise contribution lower than conventional devices because of their low loss as well as their 77K operating temperature. Please refer to our Quarterly Report #6 for a more complete analysis from a systems point of view.

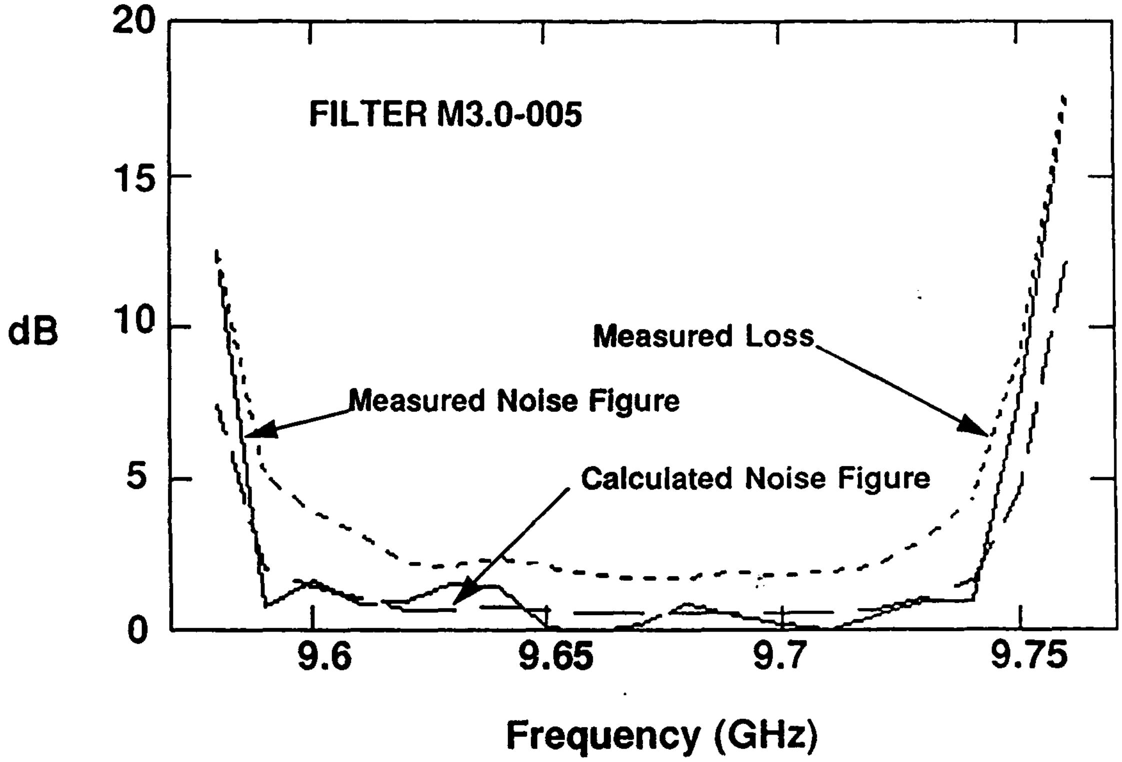

Figure 2 — Measured and calculated noise figure of HTS X-band filter at 77K. This filter, made in 1990, has a relatively high loss of 3 dB making it easy to differentiate between loss and noise figure.

TASK 2.2: FUNCTIONAL COMPONENT AND SUBSYSTEM DESIGN, FABRICATION AND TESTING

Filterbanks

- Microwave CAD Design Considerations

In this quarter the problem of a lack of adequate microwave CAD software for filter design has been addressed. We have used the 4-pole Chebychev filters being designed for the parallel HTSSE-II program as the working models for determining the CAD requirements. The results will be directly applicable to the filters required in this program. The filter structure chosen for this and the HTSSE programs has been microstrip, parallel-coupled resonators. This choice was based on our success in previous Air Force and Navy programs requiring X-band filters. Working at 4 GHz, however, we find that the geometrical designs produced by standard CAD software are suboptimal. The reasons for this are probably related to the high dielectric constant of $LaAlO_3$ and the low coupling required between parallel resonators needed for narrow bandwidth responses (1 to 1.5%). We have acquired the electromagnetic field solver **em**^{TM} from Sonnet Software Inc., which yields analyses of our structures in rather close agreement with our measurements. Examples of this were included in our Quarterly Report #6, with analyses of two of our filters made on Sonnet by the vendor. Using this tool we have already improved upon the design by synthesizing the desired 50 MHz bandwidth. A major problem remains, however; namely, the asymmetrical response with the transmission zero at the lower skirt. We are currently investigating this problem and expect to solve it in the next reporting period.

- Fabrication Reproducibility

One of the goals of this program is to achieve high reproducibility in filters and delay lines. This is critical in filterbanks for high channel-to-channel tracking and in delay lines for angle-of-arrival measurements for EW applications. During the course of this program, we are continually improving and optimizing our fabrication capabilities in the areas of film growth, processing, and packaging. Using the present filter design we fabricated four identical 4-pole filters as a measure of their reproducibility. The four responses are shown in Figure 3. As can be seen, the reproducibility is very good. Three of the filters have center frequencies within 2 MHz, the fourth is about 5 MHz low, and the pass bands are virtually identical. The distortion at the low frequency end of the pass bands, which is discussed above, is also reproduced.

- Thin-Film rf Terminations

The channel architecture to be used in this program requires two identical filters and two 90° hybrid couplers per channel. The 180° out-of-phase port in each channel must be terminated in a 50-Ω load in order to absorb the residual energy routed to this port. In order to produce a fully integrated filterbank these loads must be fabricated in thin film form. Thin-film loads and their fabrication process and photolithographic masks were designed in this quarter. For simplicity of fabrication and in order to reduce the risk of substrate breakage the loads have been designed without vias. The fabrication process has four mask levels. The resistive material is molybdenum capped with a thin layer of titanium. Figures 4 and 5 show the resistor layout and a composite of the four mask levels made for two-inch diameter test wafers. Processing on two such wafers was begun and will be completed and tested in the next quarter.

- Integrated Packaging Concepts Under Development

As explained in a previous report, niobium has been chosen for the substrate carrier material because of its thermal expansion match with the lanthanum aluminate substrate. The substrates are soldered to the gold-plated niobium carriers with indium. The remainder of the package will be made of gold-plated aluminum for light weight and because intricate machining of niobium is difficult due to its ductility and tendency to tear.

A series of indium-based solders with melting points below that of indium (155 C) was used successfully for mounting the carrier to the package and for package sealing in

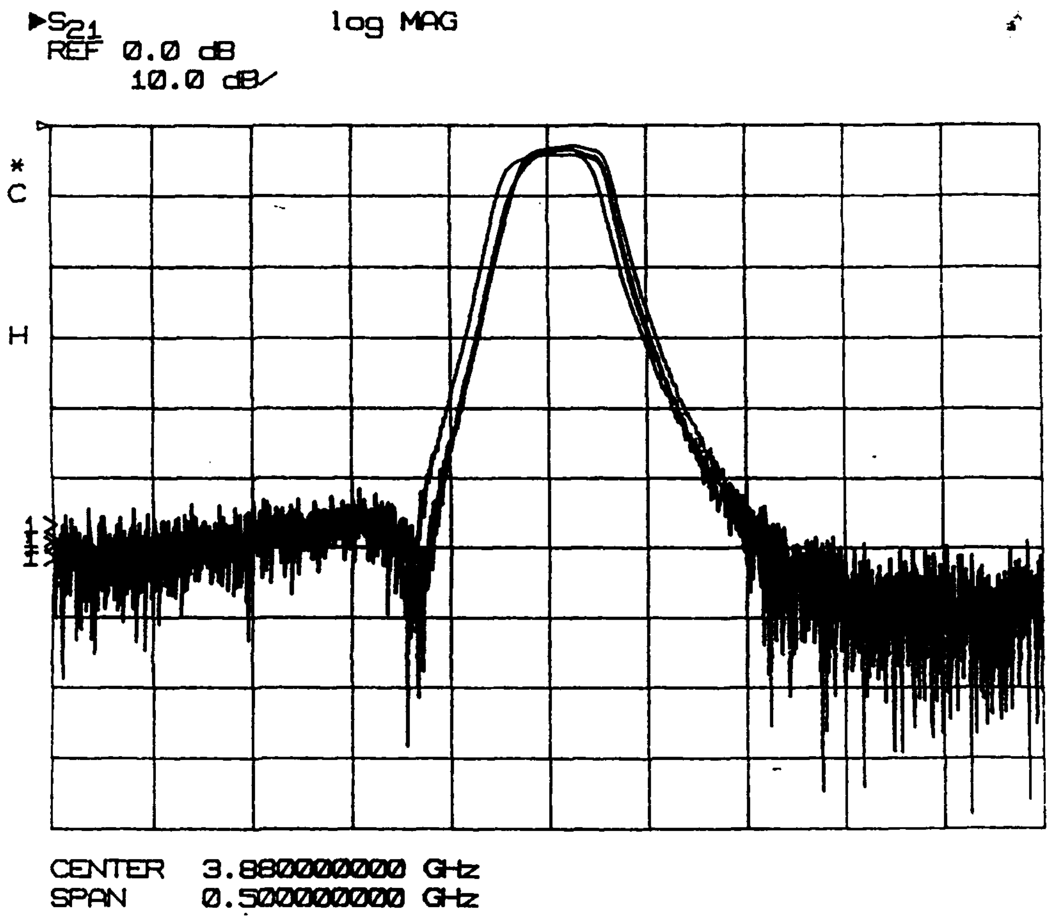

Figure 3 — Superposition of the response of four HTS 4-pole filters, showing the repeatability of our fabrication and packaging techniques.

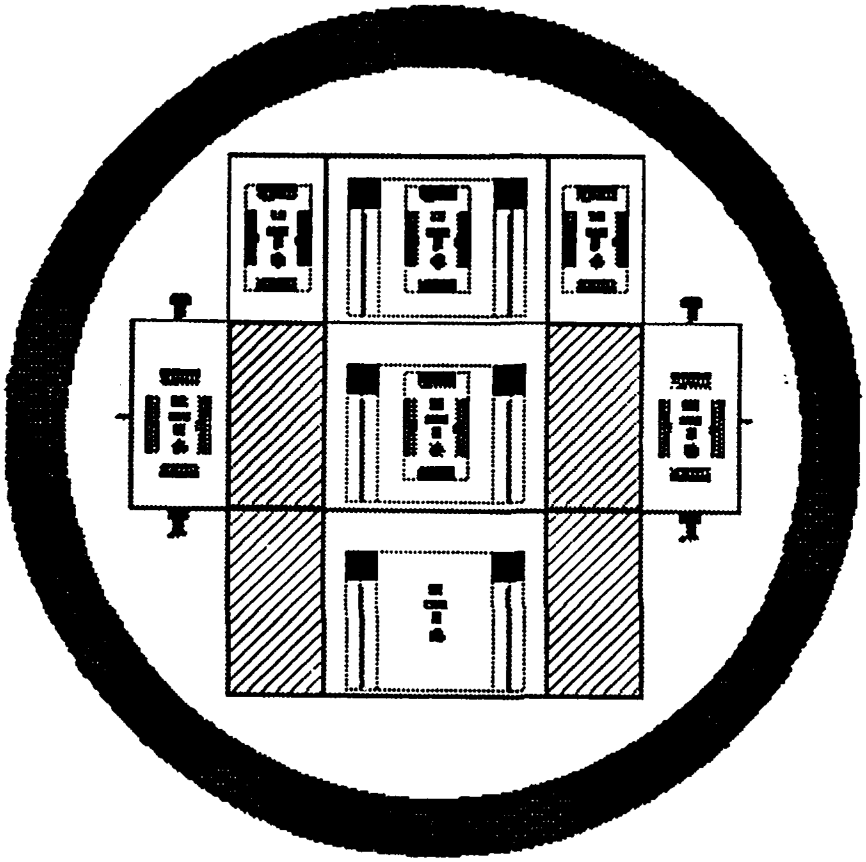

Figure 4 — Mask layout for 2-inch YBCO/LAO wafers showing the thin-film loads and various test patterns.

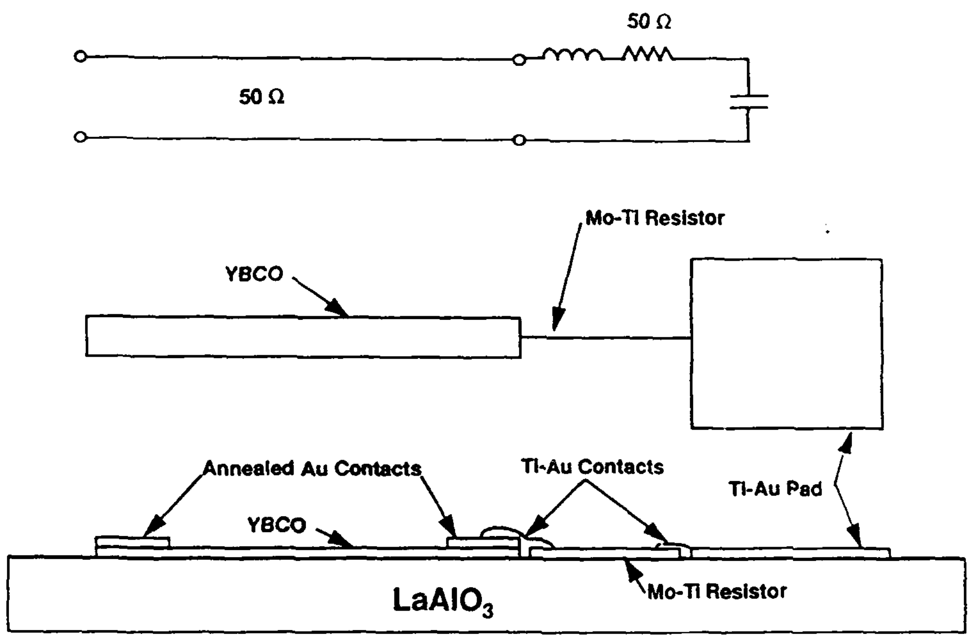

Figure 5 – Schematic diagram of thin film 50-Ω loads.

the earlier devices delivered to the Navy and Air Force. This worked very well for the small substrate filter chips which were used then. The progress to a larger integrated channelizer package with multiple substrates of larger size requires a simplified mounting scheme which can accommodate the large difference in thermal expansion between aluminum and niobium. Consultation with package engineers at Westinghouse ESG resulted in a design incorporating beryllium-copper spring finger stock around the edge of the carrier. This provides the necessary ground-plane electrical connection while accommodating the larger shrinkage of the aluminum package around the niobium carrier. It also facilitates changing the substrate/carrier assemblies in the multiple channel package during testing.

The multiple-filter channelizer requires connection of the signal line between channels with minimal loss. In the first prototype channelizer, described in our previous report, with non-integrated (separate) filter packages for each channel, the connection was made by transitioning the signal line from microstrip to coax, exiting the filter package with a Wiltron K-connector, traversing between filters with a custom-fit coax line to the K-connector input for the next filter, and then transitioning back to microstrip on the next filter substrate. In the integrated channelizer, the transition between filters will be made entirely in microstrip. A small $LaAlO_3$ chip with an HTS microstrip line will be interposed between adjacent channel substrates in a gap in the separating wall. Parallel-gap welded gold ribbon will bridge between the chip and filter substrates. The chip will be sc1dered to its own removable carrier.

Package design features have been incorporated to minimize size, weight, and volume to optimize the channelizers and delay lines for airborne and space applications. These include gold plating of the package to minimize radiation heat input, somewhat intricate machining of package components to reduce mass for lightness and to meet acceleration requirements, and substrate/film passivation to insure adequate environmental robustness during storage. Some of these and others have been dictated by the constraints imposed by NRL for the HTSSE-II program and they have been developed on that program.

• Indium Diffusion Barrier Experiments

The ground-plane sides of all $LaAlO_3$ wafers coated with YBCO films for delay lines or filter channels are bonded to a niobium carrier with indium solder for both mechanical support and electrical contact. Since solders do not make low-resistance contacts to YBCO and, in fact, attack the YBCO surface by removing oxygen, electrical contact to YBCO ground planes are made by deposition of a Au layer followed by an anneal in oxygen at 550°C and coverage by a second Au layer. However, In and Au alloy rapidly at room temperature, so a titanium layer has been used as a barrier to diffusion of In. Superconducting transition measurements of YBCO/Au/Ti/Au/In structures indicated that the diffusion barrier performed as intended. Measurements of R_s are planned that will be more sensitive to a possible low level of YBCO film degradation.

Delay Lines

The original delay line design was based on a 150-cm length of 50-Ω line defined on YBCO on a 2-inch diameter, 0.010-inch thick $LaAlO_3$ substrate. The configuration chosen is stripline which makes the 50-Ω line very narrow, i.e. 22 μm. In order to reduce the risk involved in processing such a long, narrow line, we have modified the design by widening it to 150 μm (25 Ω). Tapered sections of line are included at the ends as impedance transformers between 25 and 50 Ω.

In addition, in order to minimize the deleterious effects of an air gap between substrates on the delay performance (see previous report), we are currently developing a design that employs mirror image patterns on the facing top and bottom substrates. This will require precise registration between patterns and an assembly technique and package are now being designed.

TASK 3.1: PVD MULTILAYER FILM FABRICATION

The two subtasks scheduled for this reporting period required delivery of YBCO films on both sides of two-inch diameter substrates to Task 2.2, and development of a multilayer deposition capability on four-inch wafers.

A production schedule was charted in April, 1993, for this program and HTSSE II which called for approximately 80 two-inch diameter wafers to be coated with 400 nm thick YBCO films on one or both sides between May and October, 1993. So far, film production has stayed ahead of fabrication requirements. As anticipated in the last quarterly report, the only variable in the production process that has prevented a 100% film yield is the homogeneity of YBCO sputtering targets. A total of four targets, approximately one of every five, have been returned to the supplier. Since defective targets can be identified in their first use, each case has affected just one day in the film production schedule.

Several sources for 2-inch-diameter YBCO films have been identified which could serve as a backup to the chamber in which films are now produced. The primary backup is a second chamber at Westinghouse, nearly identical to the first, which is mostly committed to other programs. Availability of a second backup was confirmed by purchasing six YBCO-coated wafers from Conductus and measuring R_S for the four of them grown on 0.020" thick substrates. Although R_S values were within the usable range for our devices, the films were covered with a high density of CuO "boulders," which may compromise the filter performance from the standpoint of nonlinear distortion.

Spot checks continue to be performed on the surface resistance of 2-inch diameter films. Approximately a half-dozen films produced for the STALO development program were tested in a dielectric resonator. Approximately a dozen other films produced specifically for this program were checked with an end-wall replacement technique in a cylindrical cavity at 77K. In all cases, the films have been found to be qualified for use in the program.

A low level of effort was expended in the development of YBCO-coated four-inch wafers using a new sputtering chamber which can accommodate 2, 3, or 4-inch wafers. It was built to a Westinghouse design by Nordiko Ltd. Although modifications to the thermal design had reduced the heater power needed to maintain the desired substrate temperature from an initial value of 70% to less than 30% of the heater's 2.6 kW maximum, rotary feedthroughs in the vicinity of the heater were overheating during long deposition sequences. Nordiko re-designed these feedthroughs so they are water-cooled, rebuilt them, and will deliver them to Westinghouse in August, 1993.

TASK 3.2: MOCVD MULTILAYER FILM FABRICATION

Work under this task was performed at EMCORE on YBCO film growth, at Northwestern University on the development of new Ba precursors for YBCO and growth of epitaxial insulating films, and at Westinghouse STC where measurements were made of the rf surface resistance of YBCO films. However, during this reporting period no YBCO films were delivered to Westinghouse, thus no R_s measurements were performed.

Northwestern University has fabricated three generations of Ba precursors during the course of this program. The first-generation precursors, $Ba(thd)_2$, were in use worldwide at the start of the program and are still used in most MOCVD growth of Ba-oxide compounds despite its low vapor pressure and chemical instability. Since the commercially available form of this precursor has a low purity, a high-purity 20-gram batch was synthesized at Northwestern and has been in use at EMCORE for the last six months.

A 20-gram batch of the second generation precursor, $Ba(hfa)_2$-tetraglyme (hfa = hexafluoroacetylacetonate), was also delivered from Northwestern to EMCORE early in 1993. This compound has a wide temperature range in which it is stable and has a high vapor pressure. However, it was decided that the baseline process at EMCORE was not sufficiently under control to adequately test whether fluorine from the Ba precursor would be incorporated into YBCO films. Even if, as expected, there was no fluorine doping, additional measures were needed to purge HF from the MOCVD system exhaust gas. With development of a third generation of stable, high-vapor-pressure Ba precursors during this reporting period, there is no longer a plan to test the fluorine-containing $Ba(hfa)_2$-tetraglyme.

Film growth and Ba transport with the new precursors, bis(tri-butylcyclo-pentadienyl)barium, $(Cp^tBu_3)_2Ba$, and bis(di-butylcyclo-pentadienyl)barium, $(Cp^tBu_2)_2Ba$, were tested at Northwestern by depositing $BaPbO_3$ films. High precursor volatility and clean vapor transport were demonstrated at 110°C, a temperature comparable to those used for Y and Cu precursors. These compounds are solid at room temperature but, in contrast to the earlier generations, liquefy before their vapor pressure is high enough to be used. Liquid precursors have the best reproducibility because they heat evenly and maintain a constant surface area. The only drawback for these precursors is instability with long-term exposure to atmosphere. This should not be a practical limitation. A paper on the new precursors has been prepared for publication. A 20-gram batch of this new Ba precursor will be prepared and sent to EMCORE as soon as EMCORE is ready to use it.

Papers have also been prepared for publication on MOCVD of epitaxial insulator films compatible with multilayer HTS circuit structures: $NdGaO_3$, $YAlO_3$, $PrGaO_3$, and Sr_2AlTaO_6 (SAT). These films have all had good structural and electrical properties, comparable to sputtered or laser-ablated films, when grown directly on single-crystal insulating substrates. However, they are useful only when they are grown on YBCO films and subsequently serve as substrates for another YBCO film layer. So far, in contrast to sputtered or laser-ablated epitaxial insulators, they react with YBCO.

The work at EMCORE on two-sided deposition of YBCO films is behind schedule. Modifications to a reactor dedicated to YBCO growth on a 5-inch diameter substrate holder were completed by the start of this reporting period. It was moved to the same room where reactors dedicated to $SrTiO_3$ and low-ϵ insulators for the HTS MCM program are housed. However, YBCO film quality in the new chamber has not reached the same level as achieved in 1992.

TASK 3.3: RF CHARACTERIZATION OF FILM PROPERTIES

Three techniques continue to be used for R_S measurements. The most important one for this program is a cylindrical copper cavity designed for two-inch diameter wafers (end-wall replacement technique). Some refinements to the measurement technique were implemented during this reporting period to minimize the chance of a wafer cracking under thermal stress and to eliminate potential degradation of the sample by scratches, dust, or grease.

The other technique for R_S measurement of 2-inch wafers is the dielectric resonator used in the STALO program. Although it is not preferred to the cavity with end-wall replacement for screening films, it does provide feedback to the same deposition process as used for this program.

The third technique is a parallel-plate resonator using a pair of 1/2 inch × 1/4 inch unpatterned films. When there is room on a wafer that is processed for other purposes (for example, tests of thin-film loads), chips of this size are cut from the wafer after processing is complete and measured to determine whether any change in R_S occurred due to processing.

PROBLEMS ENCOUNTERED AND/OR ANTICIPATED

Although the start date of this program was July 24, 1991 with the approval of anticipatory spending, the contract was not signed until September 30, 1991 when the first increment of funding was received. The work effort was slowed at DARPA's request to stretch the FY92 funding through 12/31/92. However, FY93 funds were not received until March 30, 1993. These funding limitations will place the program at least six months behind schedule.

FISCAL STATUS

Amount currently provided	$3,100,000
Expenditures and commitments through 7/25/93:	2,533,346 [a]
Funds required to complete:	2,269,203
FY94 funds required:	1,800,000 [b]

a. Includes $461,826 committed to subcontractors and purchase orders.
b. Will also require six-month extension into FY95.